

Technology Requirements and Development for Affordable High-Temperature Distributed Engine Controls

Alireza Behbahani¹, Bruce Wood², Dewey Benson³, Andy Berner⁴, Bobbie Hegwood⁵,
John DeJager⁶, William Rhoden⁷, Bruce Ohme³, Jef Sloat³, Crystal Harmon⁸

¹*Air Force Research Laboratory*, ²*Pratt & Whitney*, ³*Honeywell*, ⁴*BAE Systems*,
⁵*Rolls-Royce*, ⁶*GE Aviation*, ⁷*Hamilton Sundstrand*, ⁸*Ohio Aerospace Institute*

Keywords: *Distributed Engine Control, Redundancy Management, Fault Tolerant Control, Networked Control System, Time Delay System, Smart Nodes, Data Concentrators, FADEC, DECWG, HT Electronics.*

Abstract: The gas turbine engine environment is particularly harsh with regards to temperature and vibration, and trends indicate that these conditions will continue to grow much more severe, especially in temperature. Conventional bulk epitaxial silicon-based electronics are used only in limited locations on engines today in support of instrumentation and production sensing and controls, and their use may be even more restricted by future operating conditions. This trend is moving in a direction contrary to on-going efforts to incorporate more intelligence into the engine, and to localize that intelligence as close as possible to the sensors, actuators and components to minimize the use of large wiring bundles. Current approaches allowing on-engine use of electronics typically involve some sort of thermal management technique, such as the use of liquid cooling loops, including nitrogen for instrumentation and fuel for controls, as well as convective air cooling by strategic placement of electronics. However, these passive cooling techniques are often inadequate to ensure necessary reliability and durability, and the active techniques are typically cumbersome and costly, and don't lend themselves to in-product applications. An alternative to addressing the environment in which the electronics are required to operate is addressing the robustness of the electronics themselves, in particular with regards to high temperature capability.

The Government and Industry Distributed Engine Controls Working Group (DECWG) [5] has been established to find the tools (high temperature components, modeling, software) supporting the design and manufacture of high temperature electronics required for implementation of distributed control systems that do not require cooling on gas turbine engines of the future. DECWG is currently working to define requirements for new harsh environment capable digital integrated circuits and power electronics based on Silicon-On-Insulator (SOI) material that can reliably operate at temperatures up to approximately 225°C. These high temperature capable electronics must be capable of long operational life, high reliability and especially must be available for a reasonable cost. The goal is to enable implementation of Smart Nodes that would strategically localize 'intelligence' to provide analog-to-digital conversion, basic processing and health assessment of sensor inputs, as well as generating currents from digital commands to drive actuators. In addition to the in-product Controls application, these Smart Nodes could become the basis for High Temp Capable Smart Instrumentation,

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 2012		2. REPORT TYPE		3. DATES COVERED 00-00-2012 to 00-00-2012	
4. TITLE AND SUBTITLE Technology Requirements and Development for Affordable High-Temperature Distributed Engine Controls				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Research Laboratory, Wright-Patterson Air Force Base, OH, 45433				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES Presented at the 58th International Instrumentation Symposium, San Diego, California, 4-7 June 2012					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 18	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

potentially allowing a suite of sensors to be installed on test engines by way of a digital communication network, with the intent of reducing both cost and set-up time.

This paper provides a report on DECWG's High Temp Electronics and Packaging Requirements Definition efforts for the purpose soliciting reaction from the Instrumentation community as to the applicability of these requirements to their specific interest and needs.

Introduction

A continuous goal of the aerospace propulsion community is increase engine performance and efficiency while reducing operating costs. The Air Force, Navy and Army have led such efforts under the Integrated High Performance Turbine Engine Technology (IHPTET) and currently under the Versatile Affordable Advanced Turbine Engines (VAATE) programs [5], focusing primarily on low bypass engines for military applications. Similarly, National Aeronautics and Space Administration (NASA) has sponsored the Ultra-Efficient Engine Technology (UEET) and currently the Fundamental Aeronautics, with similar goals to reduce aircraft fuel burn and greenhouse emissions, primarily for large bypass engines for Commercial transport aviation applications. Both Department of Defense (DoD) and NASA programs recognize that one important means to achieve their goals is drive more intelligence into the operation of the gas turbine engine. This effort has its roots in the introduction of digital electronic engine controls to aircraft engines in the 1980's, and continues to expand, following but unfortunately lagging the integration of computing power into numerous consumer products.

The primary challenge to the advancement of Intelligent Engines is the particularly harsh operating environment present in and around the gas turbine engine. In order to realize the necessary performance and efficiency metrics, gaspath temperatures now reach several thousand degrees of temperatures. Even with the latest sophisticated cooling techniques, the outside case temperatures of today's gas turbine engines where the computing devices would be located are several hundred degrees; well in excess of the maximum temperature capability of most of today's silicon-based consumer or industrial grade electronics. Various techniques are being used to overcome the challenge of placing computing capability in such a harsh environment.

One approach to address the problem of harsh environment computing is to locate a Full Authority Digital Engine Control (FADEC) as far away from the heat sources as possible, as in the case of Commercial Transport Engine, where the FADEC is mounted on the Fan Case, well forward of sources of heat generation. Unfortunately, this solution places the computing capability far away from most of the sensing and actuating components. Large wiring harness bundles are required to interface the FADEC with these sensing and actuation devices. The size of these harnesses is driven by the need to ensure the quality of analog signals passed between the computer and the devices, both in terms of maximizing analog signal strength and minimizing interference and noise. In a number of applications, the resulting robust wiring bundle has been so heavy and costly that it actually cancelled the benefits that the additional intelligence was intended to provide.

Another approach to address both the problems of computing in harsh environment and reducing the requirement for large numbers of heavy analog wiring harnesses is to locate the FADEC in a more centralized location, and to apply some type of forced cooling to manage the operating temperatures in and around the computing electronics. Military fighter aircraft engines have significant constraints on

size and volume, and as a result, few options for locating computing away from high temperature heat sources. Fan compressed air is often flowed around and cold fuel is sometimes flowed through a more centrally located FADEC as means of dissipating heat away from the electronics. This approach however introduces its own problems associated with the complexity, weight, cost and reliability concerns associated with forced cooling systems. For both the high and low bypass engines, extended ground operations are a particular challenge, where the cooling sources are less effective, and engine soakback heat tends to pose a significant temperature challenge to the computing electronics.

An alternative solution to addressing the environment around the FADEC is to increase the temperature robustness of the electronics and packaging itself to be adequate for the aircraft engine application. With high-temperature capable digital electronics, intelligence can be located very near, even integrated into the various sensors and actuator that make up an engine control system. Analog-to-Digital and Digital-to-Analog conversion can take place at the point where the signal is generated and/or used, allowing implementation of a lighter, smaller, less costly and more reliable digital communication network. Such devices would serve as Smart Nodes, and could be located individually or in groups – in the form of Data Concentrators – around the engine, as appropriate.

High temperature capable silicon-based electronic devices are being developed which could be used for these Smart Nodes, with temperature capability on the order of 250°C for Silicon-On-Insulator (SOI) type components, and 500°C for Silicon Carbide (SiC) type components. Some of these components are in production today, especially for high end applications such as for satellites, where the premium cost is justifiable. However, such is not the case for aircraft engines, where product cost is a significant factor in the overall business case. The market for high temperature capable electronics is currently much smaller than for room temperature capable consumer electronic components, and the disparity in cost of the electronics reflects the difference in market size.

In 2007, a Distributed Engine Control Working Group (DECWG) [5] was formed by members representing the DoD, NASA, aircraft engine manufacturers and their engine control suppliers to explore possible solutions to the challenges associated with integrating more intelligence into gas turbine engines for aircraft applications. Certain approaches were identified as candidates for pre-competitive collaboration, particularly those where an industry working group might have more success in driving new options, than any one company individually. DEWCG is assessing the aerospace propulsion industry needs for “smart” sensors and actuators, to establish goals for minimum computing capability and temperature robustness that would enable architectural changes in the way that engine control systems are implemented, to be able to move away from thermally-managed centralized FADECs to more product-optimized Distributed Control architectures.

One focus area is the previously mentioned high-temperature capable electronics. Certainly, the relatively small aerospace computing electronics market is not a major driver for business decisions made by electronic component supplier industry. But overall market-driven trends towards “smarter” consumer products is slowly moving the electronics industry towards higher temperature capable electronics and packaging. In addition, it is expected that significant improvements in electronics power consumption efficiency that can be realized through the use of advanced electronics such as SOI may help accelerate this trend. By indentifying the lower temperature bounds of what computing capability would be necessary to allow implementation of Distributed Control architectures for gas

turbine engines; DECWG is working to close the gap with readily available and inexpensive consumer electronics market.

DECWG is completing an Air Force funded project to document the current state-of-the-art and establish both overall Engine Control System and individual Smart Node level requirements for electronic and packaging components that would allow implementation of Distributed Control architectures. These requirements are specifically targeted towards the somewhat uniquely harsh gas turbine engine for aircraft application environment. Both technical and cost targets are being established, so that trades can be made between the two. The goal is to come out of this Requirements Definition effort with a strategy as to where to focus future funding, perhaps in the form of Non-Recurring Engineering (NRE) investments that would begin to address the hard points making available affordable high temperature electronics necessary to implement the minimally-capable Smart Nodes.

This paper presents a summary of the work being performed by DECWG during the Needs and Requirements Definition effort, for the purposing of soliciting feedback and input from the larger high-temperature capable electronics consumer community. DECWG recognizes its limited ability to influence electronic components manufacturers to push the temperature capability of their products. But it is hoped through collaboration with similarly interested industries, such as Instrumentation, Industrial Foundries, Automotive and others – perhaps a niche market for affordable higher capable temperature electronics can begin to come together, offering new computing options for infusing more intelligence into each market sector's products.

Lessons Learned in Prior Distributed Engine Control Programs

Significant effort was required by Government and Industry teams to transitioning from hydromechanical to digital computer-based engine controls – a true revolution in operation of gas turbine engines, providing pilots “carefree operation”. But in the following twenty years, improvements have been more evolutionary than revolutionary. Digital engine controls are tracking and lagging consumer electronics.

Several DoD and NASA programs have attempted to accelerate enhancements to digital on-board computing supporting Engine Controls, with mixed results. Of particular note was the 1990's High Temperature Electronic Components (HiTEC) program, collaboration between Government, industry and academia to explore dual-use (military and commercial) technology development of high temperature electronics. Program goals of HiTEC were to develop and commercialize a set of high-temperature (200°C) integrated circuit components based on silicon-on-insulator (SOI) technology that could enable distributed control system architectures placing intelligence in harsh environments. Ultimately a “smart” vane actuator was demonstrated on an IHPTET experimental test engine.

While HiTEC was successful in demonstrating a “smart” node, it ultimately did not realize its goal of transitioning this technology into engine products. One significant lesson from HiTEC was that “smart” nodes needed to be able to buy their way into engine configurations. Trade studies between centralized and distributed control architectures found that the housing and power supplies required for each of the “smart” nodes actually added weight to the engine versus a single unit FADEC. Even more

important, the high cost of custom built high-temperature electronics and board packaging drove a “smart” node design that was functional, but not feasible. A simple distributed control system of a hub and just a few nodes could cost more than a full-up FADEC, with much less capability.

An important lesson learned for any similar “smart” node development activity is to establish design requirements and the business case concurrently – and actively conduct trades between the two before settling on final technical requirements. It does no good to make significant investments in a distributed control solution that penalizes rather than improves engine performance and recurring cost metrics. For example, development of a 200°C capable “smart” node may be a goal; perhaps implementation of a 175°C node provides significant benefit at a significantly lower cost.

Another lesson is that the business case should be broadly encompassing to consider the many factors influencing a decision as to whether or not to select a distributed architecture, rather than making a simple trade based on only say the comparative weights of the boxes. For example, locally-placed intelligence can significantly reduce the weight and cost of heavy analog wiring harnesses, in favor of smaller ones using only digital communication. Reuse of “smart” sensor nodes across multiple engine programs, as well as to reduce the amount of work required to address FADEC obsolescence “turns” could result in significant cost savings.

Subsequent Distributed Controls development programs have learned from these lessons. In 2001 – 2005, General Electric and their control hardware supplier BAE Systems were funded by AFRL to develop a “Flexible FADEC”, which created standard reusable “modules” that were located in a single environmentally conditioned box, rather than being spread all over the engine. Honeywell was funded through a Dual-Use Science and Technology program to design and demonstrate a “Modular Aerospace Control” (MAC) FADEC, which implemented a first generation distributed control architecture in a box, using conventional bulk silicon instead of more expensive SOI components. Hamilton Sundstrand, control hardware supplier for Pratt & Whitney, was funded to study a “Common FADEC”, which investigated means to implement a FADEC with swappable components that could be shared across engine programs.

In 2003, AFRL sought to combine these various efforts and elements into a single “Universal FADEC (UF)” idea [1]. The UF was modular, distributed (within FADEC), adaptive, standard I/O, open interface standards, standard power supply, and COTS electronics to achieve open system architecture. AFRL’s idea was to create a modular FADEC design, with both open-system hardware and software that could be shared easily across various engine applications, and different manufacturers, and also providing plug-and-play reconfigurability and upgrade capability to minimize the impact and cost of obsolescence. The thought was that FADEC commonality across industry could drive certain economies in development, acquisition, and support/maintenance costs. Unfortunately, commonality at the overall FADEC level would require major changes in the industry including sharing proprietary information and also requiring major investment. It was concluded that concentrating on important aspects of the UF, namely distributed (decentralized) and high temperature electronics would be acceptable to the OEMs and FADEC manufacturers’ future collaborative efforts.

In 2007, rather than immediately establish yet another new program to attempt to develop Distributed Controls, the Air Force Research Labs (AFRL) and National Aeronautics and Space Administration (NASA)–Glenn Research Center (GRC) facilitated establishment of a Distributed Engine Control

Working Group (DECWG). Government and industry have come together on a pre-competitive basis to examine the current state-of-the-art of engine controls, and jointly identify control system hardware requirements for future propulsion systems. Industry members explore the business cases associated with the selection of distributed control architectures, and provide that information back the group. This will allow identification and development of plans to address the remaining technical barriers to implementation of affordable high-temperature capable distributed control systems.

Technical Requirements of Distributed controls

1. Distributed Engine Control Architecture Options

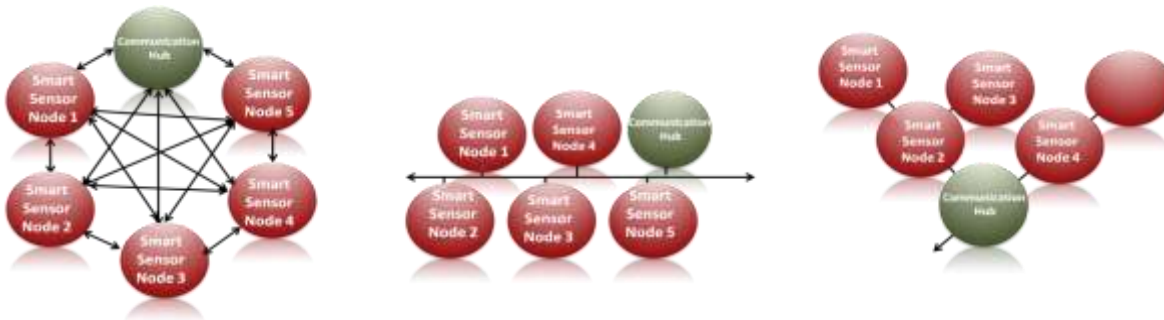
The term “Distributed Engine Control” usually refers to an integrated intelligent system comprised of more than one computing device, serving as controllers to command a suite of actuators and accessory devices, and processing inputs from feedback devices located in those actuators, as well as sensors providing information regarding the operating condition of the engine. While intelligence may be spread throughout the control system, there is typically one (perhaps two for redundancy) computers serving as the central “Supervisory FADEC” for both the high-level engine control laws, and a “Communication Hub” for managing network communication between the other various “smart” devices or “nodes”, as shown in Figure 1.



Ring Topology

Star Topology

Line Topology



Fully Connected Topology (Mesh)

Bus Topology

Tree Topology

Figure 1: Basic Distributed Control Architectures – Hub and Nodes

Typically, higher-order functions such as execution of Control Laws or managing communications internally as well externally to the Distributed Engine Control network require significant computing

capability. Distributed Control Architectures [2, 6, 7, 8] would place these “Supervisory FADEC(s)” devices (for redundancy purposes) in as benign a location as possible on the engine, or even more them off engine to an appropriate location on the aircraft. The Communication Hubs will be possibly attached to a small computing capability referred as “Intelligent Hub” or also referred to “Smart Data Concentrator”, or call it “Intelligent Hub/Data Concentrator” to reflect some basic fail-safe capability. The remaining devices would serve as smart nodes supporting the hubs, performing functions locally near the sensor and/or actuator. For purposes of this paper, there are three configurations of “smart nodes”. One is a “smart sensor node”, which could be co-located with one or more sensors, performing basic analog-to-digital signal conditioning, signal quality checks and communication. A second would be a “smart actuator node” that would perform functions similar to the “smart sensor node” with regards to the actuator feedback signal, plus would perform local “loop closure” to generate analog commands for the actuators, as well as perform basic fault detection and accommodation. A third type would be a “Intelligent Hub/Data Concentrator” module, which would be used to concentrate and exchange information between the Supervisory FADEC and the smart nodes. The sophistication of the computing for each type of node would be appropriate to the task that they are required to perform.

There are a number of topologies by which the primary “Intelligent Hub/Data Concentrator” controller can be the interface with the various remote nodes. These include ring, mesh, star, line, tree, bus and fully-connected structures, as shown in Figure 1. Robustness and redundancy must be a consideration when designing these networks, a single failed node or communication link should not be able to take down the entire distributed control system. Adding robustness and redundancy, such as a braided ring topology, can further complicate the distributed control communication network.

Note that any number of communication protocols can be used with the various network topologies. The key is that computing capability in the nodes must be able to support whatever protocol is selected. DECWG is currently investigating the applicability of three different communication protocols, representing the range of what be implementable on nodes with minimal processing capability. These include a Simplified TT-Ethernet utilizing a standard IEEE 802.3 communications layer, a modified +1Mbyte Multi-Drop RS-485, and a deterministic CAN bus. It is not the intention of DECWG to select a particular bus protocol for all application, but rather to ensure that adequate computing capability is available in the nodes to support at least several different protocols

2. Data Transfer Management

In traditional centralized control systems, overall system behavior is governed by the deterministic timing in the centralized FADEC. The centralized unit receives all of the sensor data directly, translating analog data from each of the remote sensor and actuators nodes into digital data. In such systems, all data arrives within a known timing frame. Many data management tasks, such as identifying the source and time of a measurement, are inherently simpler due to the centralized architecture. based on the assumed properties of point-to-point communication links.

In a distributed control system, the behavior is determined by the management of data transfer between the nodes and must be more structured. Instead of single unit acting on the information acquired from sensors, multiple data generators and users will co-exist on a distributed network. All the nodes on a network will have access to information from many sources. Time delays of data through the network must be taken into account in assessing control loop stability. Network protocols and timing must

support the deterministic requirements of the control system behavior. Data latency analysis is already commonly employed in centralized engine control systems. Similar methods will be employed to schedule data collection and transmission through the networks to achieve the deterministic and stable behavior needed.

A number of techniques can be used to manage the data. In many cases, on-board engine models can be used in the absence of actual physical measurements to synthesize sensor values. It is necessary to include the value or a reference to the value in the data sent from a distributed node for any item normally inferred from the properties of a point-to-point link in a traditional system, e.g., source node identity. The minimum elements of data include attributes for the value, units, time, the location of measurement, and identification of the parameter measured. Depending on the complexity and capability of the smart node, other information such as accuracy or precision may be included.

3. Network Interfaces for Data Concentrator

The network interface protocols will define all features of the smart node data packets.. Data packets, network connections, and node behavioral models are specified by the network interface. The use of common protocols for each smart node type allows the design of nodes that can create and operate on the data packets without further configuration. The main purpose of the data packet definitions is the network-level deterministic representation of the various data. This representation includes parameter value, units, time of data taken, calibration and module specific data, engine specific data, health data and hot zone (place of measurement) environmental data. The data is communicated and can be received by all nodes in the multicast group. The Data Concentrator will filter, identify, prioritize, evaluate and synchronize smart sensor information along with the health before transferring to the supervisory FADEC.

The data concentrator will validate data from sources and provide validation wrappers on sent data on each serial data bus. The Data Concentrator can provide calibration or conversion to standard units and even combine data into useful variables to relieve the simpler nodes of more rigorous math routines. It will therefore “concentrate” the data which will be combined into well defined packets for communication to other computing resources or supervisory FADEC. The data concentrator may facilitate data source selection for the system. The Data Concentrator will also provide local loop closing capabilities for parameters such as actuator position.

4. Smart Node Interface

A smart node data bus and the associated data packet definitions will serve to enable all features of the smart node. The data packet definitions will include a superset of sensor and/or actuator features. There are four areas of concern: the physical form of the interface, identity specifications, operational specifications, and calibration specifications. The physical form of the interface includes definitions for sensor and actuator signals, including sensor excitation levels and actuator voltage, current and power levels. It will specify preferred wire usage and preferred connectors. Also included in the physical aspects of the smart nodes will be the physical aspects of the serial data bus including signal levels, common mode voltages data rates, preferred wire types, termination, preferred connectors and possibly even preferred pin assignments. Provisions should be made to allow for a unique identifier that allows

the smart node to determine node changes including, potentially, whether the transducer has been changed. The data packet definitions will enable the manufacture's identification for each smart node or smart actuator. The smart sensor or actuator operational specifications of the prototype include the minimum sampling interval, transducer warm-up time, acquisition time, units, data representation, precision, and accuracy. The calibration specification includes the method and parameters to enable the physical transformation needed at the supervisory FADEC or in the computing resources. Other calibration data including the component health status, useful life may be included here. To allow for recalibration, these items are stored in non-volatile memory within the various smart nodes.

5. High Temperature Smart Node Level Requirements

“Smart” nodes supporting Distributed Engine Control architectures [2, 3, 7, 10] not only have to meet basic functional requirements, but must also meet environmental robustness requirements, as a function of where they are intended to be used on an engine. An approach for analyzing the design requirements for the use of smart sensors and smart actuators is shown in Figure 3, where the temperatures present on the engine case are profiled for various current and future engine products. Since it is currently not feasible to design smart nodes that can be used in any location throughout the engine, where temperatures can reach thousands of degrees, decisions have to be made as to what range of temperature capability does provide significant value to implementing distributed control architectures. DECCWG has decided to design nodes to a single, rather than a number of different maximum temperature capabilities, in order to limit the number of new high temperature capable electronics and packaging parts that need to be created.

The initial temperature target selected by DECCWG is 225°C, driven primarily by the capability of the Silicon-on-Insulator (SOI) electronics. This range would allow smart nodes to be distributed in many, but not all desired locations around the engine. At the same time, a cost target of \$500 per node has been established to bound the solution set to provide “smart” nodes that are affordable. It is understood that as an assessment of available components continues, both the temperature and cost targets may need to be modified in order to meet the business case for use of “smart” nodes in control architectures.

Based on this high-level target, DECCWG has begun to define specific requirement for the individual components required to construct smart nodes.

One means that can be used to help drive down cost is to pursue standardization of the various components that would go into a “smart” nodes. This is not an attempt to create and force use of a standard “smart” node across industry, but rather to make the critical parts available so that industry has the ability to create affordable high temperature capable nodes. This approach does not dictate a communication protocol, but provides the electronics to enable implementation of a number of them

These requirements are most suitably supported by consistent and flexible system solutions, which are scalable for different applications possibly some applicable to commercial applications. These requirements will be verified and validated by the OEMs and FADEC manufacturers in the near future. Consistent use of standards, e.g. in communication, ensure seamless and interoperable systems that eventually reduce the cost of distributed control for both the system developers, and system users. In

today's Centralized FADECs, most segments of the FADEC, are designed and developed at the OEMs with their preferred FADEC manufacturers. However, the distributed control of the future will be based on components designed and developed by different components developers and manufacturers, and will be integrated by the FADEC manufacturers and the OEMs for a specific manufacturer. There are needs to develop high temperature ASICs and high temperature FPGAs that are yet to be designed and tested, to incorporate these requirements. Another critical area in any distribution controls are the PCBs where the electronic components are being assembled. Therefore, the smart node supply chain of the future that develops distributed controls will require a migration and modernization strategy for future engine controls. One of the benefits of having specialized, dedicated high temperature components is that the supplier base will be suited to support the multi-decade life of a typical engine controller, thereby alleviating the continuous cycle of obsolescence upgrades that often result in more development investment than did the original FADEC development effort.

The architecture [8] will define interfaces, protocols, parts requirements, and certification requirements. The initial effort is defining the requirements needed, developing component manufacturing processes and conducting an engineering investigation of distributed control architectures utilizing high temperature electronics. The scope of the investigation is bounded by a 225°C temperature limit and a cost target of \$500 per module. To date, technical data supporting the availability of parts and processes needed to construct the physical architecture is lacking. The initial effort investigates the feasibility of constructing the defined architecture given the parts and processes today. So far, the parts and processes are not adequate to construct the desired architecture's physical layer. The initial effort outcome will be an evaluation of parts and processes available today compared to the requirement. The initial effort outcome will likely lead to work on component durability, mounting techniques for high temperature components to include adhesives, high temperature board materials and fabrication and supporting technologies like solder masks. The evaluation also will give insight into parts available and their durability. Part durability is not expected to meet aerospace industry expectations, giving insight into the lifing gap. The part cost evaluation will also give valuable insight into how far off the current costs are compared to the requirement. The initial effort outcome is critical to a productive and successful ongoing effort. The goal can only be reached by knowing the current state and focusing resources on the shortfalls identified in the initial effort program.

Specific High Temperature Capable Smart Node requirements are being finalized by DECWG from gas turbine engine control perspective. These can be made available to other interested parties for review and feedback on request.

A block diagram of the future distributed FADEC control system architecture [7] is shown in Fig. 2. As the block diagram shows, the distributed architectures of the future will consist of "Smart Nodes" (SN) which manage the real world devices such as sensors and actuators and communicate over data

buses with higher elements of the echelon such as Data Concentrators and supervisory FADEC.

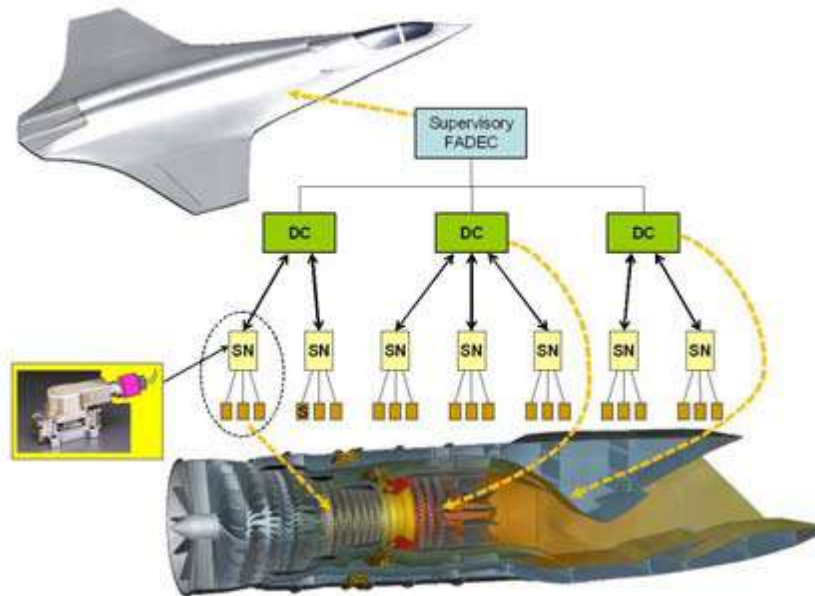


Figure 2: Smart Nodes with Data Concentrators for a Distributed Control

6. Operational Aspects of Smart Nodes

The internal operation of the smart nodes may be divided into two phases; start-up and normal-operation. The start-up phase occurs after power-up or reset. During the start-up phase, the following sequence of events takes place within the node: The transducer uploads the information contained in the “electronic data sheet”. Based on this information, the node configures itself as a sensor or as an actuator. In addition, it configures the physical transformation, as well as operating characteristics imposed by the transducer, for example, warm-up time and minimum sampling interval. Thus it is possible to completely change the nature of a node by substituting a different transducer. For example, a temperature transducer could replace a pressure transducer or perhaps another temperature transducer with lower accuracy. These changes are reflected automatically in the transducer-related node behavior. Based on the information received by the node, the node configures the application transformation. The node monitors the network to detect the presence of other nodes. Based on the information received, the node configures the relevant properties.

7. Packaging Considerations

Printed Wiring Boards (PWB)

There are many problems related to creating a cost effective high temperature capable distributed jet engine control system. The manufacturing problems range from the electronic devices themselves (op amps, analog to digital converters, FPGAs, memories, etc.) to the interconnect boards that route the traces between these devices to create a complete electronics module. Currently, the standard

approach for creating long lasting, high temperature modules is to use high temperature electronics on ceramic modules. The electronic components are “brazed” onto the module. The brazing process is similar to welding and while it produces an extremely durable bond, it is an expensive and difficult process that does not lend itself to rework. This section focuses on the need to change from the ceramic module with “brazed” parts, to a more conventional PWB technology that uses more conventional form of soldering.

Ceramic brazed modules are expensive, brittle, and difficult to manufacture and rework. Because of the cost of these modules, and given the cost targets for a single module given to DECWG, the current technologies are not viable. Current state of the art PWB technologies used in conventional temperature engine controls are not capable of surviving in the harsher environments that the new distributed engine controls will be subjected to. Current FADEC technology yields ~50,000 hours of life in a -55°C to 100°C environment (125°C device junction temperature) in convection cooled commercial engine applications and ~25,000 hours of life in fuel cooled military engine applications. The estimated environment for the new distributed engine control system is shown below:

Steady state Operating: 140°C

Soakback: 170°C

Low Temp extreme: -55°C

Delta Temperature (worst case): -20°C to 150°C

PWB: 200°C hot spots, 175°C typical operating, 6-10 layers

The estimated operating profile (shown in Figure 3) shows a typical thermal profile for these modules. It is our engineering judgment that some modules will be in “cooler” areas and will see the worst case

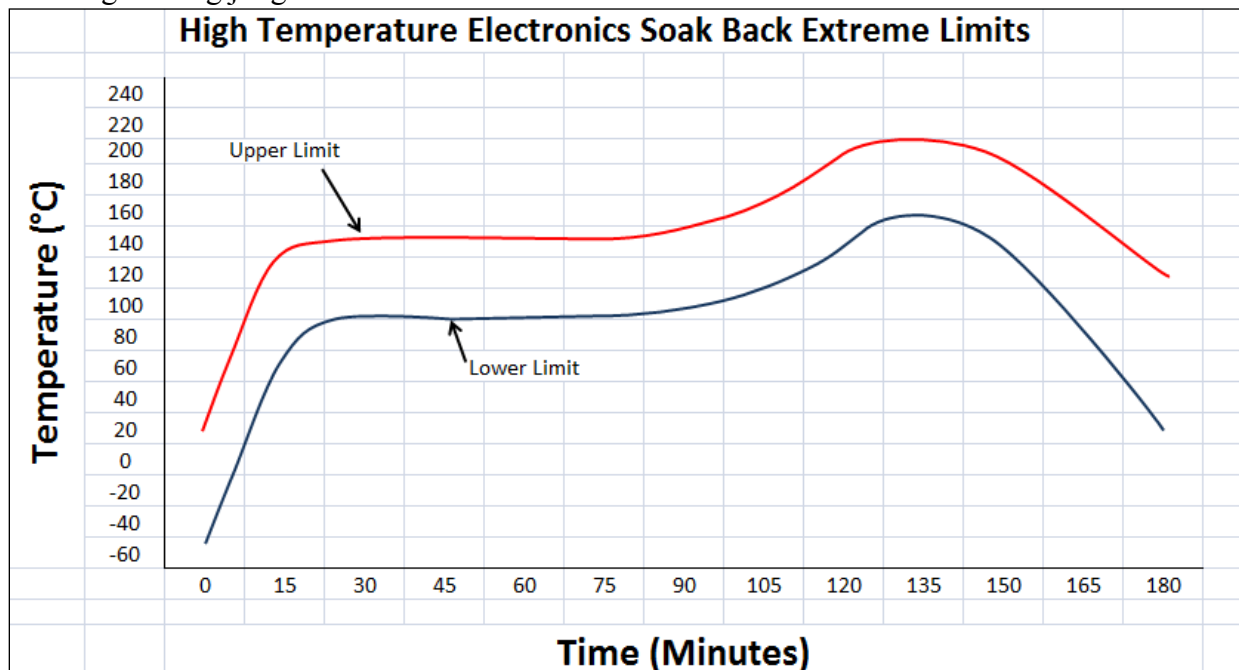


Figure 3: High Temperature Electronics Soak Back

minimum temperature (-550C) but not the worst case maximum. Other modules will be in “hotter” areas and will see the max temperature (1400C operating, 1700C worst case) but will not see the worst case minimum temperature. The profile shows the warming cycle that occurs as an engine and the module warms up to a steady state “normal” operating temperature. After the engine is shut down a thermal condition known as soak back occurs. Soak back is a rapid temperature rise that happens because all sources of engine cooling (cooling air flow or fuel cooling) get abruptly shut off and all of the thermal load of the engine and the self heating of the modules “soaks back” into the system. While this is only a transient condition, does occur to varying degrees of severity on every engine cycle. After this soak back state the modules then start to cool off.

The key areas of concern from the module fabrication and life perspective are defined by the following characteristics:

Steady state Operating Temperature
Soak back (or High Temp extreme)
Low Temp extreme
Delta Temperature (worst case)

Conventional PWB are typically built using laminate materials manufactured by specialized producers of these materials (vendors like Arlon, Nelco, Isola, Rogers, etc.). The different laminate materials are designed to deliver differing levels of performance in many key parameters. These parameters determine a laminate’s ability to withstand differing ranges of temperature cycles, how much they expand and contract over temperature, how much moisture they absorb, and many other performance concerns. Table 1 (below) will demonstrate how the requirements of the high temperature modules differ from the requirements of the current modules.

TABLE 1: High Temperature Module Temperature Requirements

Parameter	Current	High Temp	Delta
Steady state Operating	85°C	140°C	+55°C
Soakback(Max Temp)	100°C	170°C	+70°C
Low Temp extreme	- 55°C	- 55°C	0C
Delta Temperature (worst case)	80°C	130°C	+50C
PWB Hot spots	120°C	200°C	+80C

A key parameter for PWB laminates is the glass transition temperature Tg. At this temperature the thermal expansion of the laminate increases rapidly. This rapid change will cause extreme stress to the module which results in broken interconnect traces, cracked vias and other PWB related failures. For some of the PWB technologies available, the glass transition temperatures is dangerously close to our “normal” conditions of steady state and soak back. During the board assembly process great care is taken to minimize any exposure to the glass because of the stresses it presents to the PWB. To have a PWB continuously exposed to these stresses would rip it apart quickly.

DECWG is looking at starting to investigate current laminate technologies to determine if they are able to survive the anticipated environment

Interconnect Technologies

The interconnect technologies used to construct a printed wire board are another key factor that determines the long term life of a PWB module. Interconnect technologies is a term used to describe the types of structures used for pin to pin and device to device connections. These technologies include PWB traces, planes and vias (these include: through, blind, buried and microvias). The size of the internal vias, the thickness of the interconnect traces, the number of layers in a PWB, and many other factors tremendously influence life. For example, a PWB that is 6 layers+ thick and uses 22mil diameter vias will probably last 50,000 hours. If you increase the number of layers to 24 and change nothing else, the life will probably only end up to be ~10,000-15,000 hours. DECWG will evaluate have four (4) layer boards and use low density interconnect techniques. Microvias and other advanced PWB interconnect technologies need to be investigated.

Solder Technologies

Solder technologies are another area that needs more development. Differing solder metallurgies solder volumes, and stenciling techniques have great impact on the total life of the module. If a PWB module can be designed to survive the high temperatures and extreme thermal cycles, the next most likely source of module failure will be solder joint failures due to fatigue. There are many different solders available on the market, each with differing tradeoffs in performance. As is the case with the PWB laminates we need to evaluate more solders and solder techniques and we may need to develop new solders that are designed to meet the unique requirements of the high temperature distributed system.

Solder Masking and Conformal Coatings Technologies

Some other areas that will also need to be studied and evaluated are in the areas of solder masking and conformal coatings. At present, DECWG has not found any solder mask materials that can survive our environment. This is a disconcerting issue since solder masks are a key element to providing protection to PWB surface features like surface traces, vias and device pads. The module level material that needs to be investigated for its ability to survive the high temperature, high delta T environment is the conformal coat used on the modules after assembly. Conformal coatings are needed to provide a uniform dielectric between the module and the surrounding environment. When a conformal coat is used that is not appropriate for a given environment it can increase moisture related failures, increase solder joint failures and can be inadequate to protect against dendrite growth and tin whiskers.

8. *Failure Management and Reliability*

As the functionality of air vehicle systems become more intricate and the control systems needed to management the gas turbine engine become more complex the ability to operate and maintain modern engine control systems can become a high burden to the air vehicle operator and a task overload to the air vehicle pilot during non-optimal operation of the air vehicle during a failure situation. From an air vehicle maintenance standpoint the gas turbine engine is, for obvious reasons, the most complex Line Replaceable Unit on the vehicle accounting for a majority of the maintenance cost on an aircraft. Life cycle costs in the civil market, as well as mission readiness in defense applications also affect the

overall reliability of modern aircraft. Regardless of the complexity of any air vehicle, be it civilian or military, safety of personal and protection of high dollar assets are paramount. In the Civil market, the inability to dispatch due to a single component function loss places a burden on operators in terms of asset availability and thus operational margin. On the defense side the inability to dispatch if part of the electronic control system is in-operable has security as or serious affects. In this area distributed control systems have the ability to add to the current readiness and safety of safety critical aircraft propulsion systems. In a distributed control system an architecture which allows for dynamic function re-allocation to other smart devices, which is possible because engine control system functionality have been distributed to separate devices, allow for control system function reallocation via one of the high speed communication bus, especially if the failure is related to a logic or computing device. For life cycle maintenance costs, quick failure isolation and identification affects the ability to place the air vehicle asset back into operation service. Because of the inherent dynamic system re-configuration capability that a distributed control system can bring, the ability to maintain and increase the safety, availability and maintenance allow distributed control systems to bring value added capability in an air vehicle.

9. Certification Issues

As has been inferred in prior paragraphs, the high-level engine control law logic may no longer be physically located on the engine, when a distributed architecture is implemented. It instead could be co-located with other aircraft flight critical functions, such as the flight control laws or common avionics computing resources or supervisory FADEC. Such co-located processing of engine and flight control functions opens the door for greater integration of both aircraft control and fault accommodation functions.

One of the challenges for this type of functional integration is to address Federal Aviation Administration (FAA) regulation that require engine operation to be independent of all other aircraft functions, such that if other major aircraft systems fail, the engines remain unaffected. The purpose of these rules is to mitigate cascading failures that could ultimately have catastrophic results. Current FAA regulations require that the engine manufacturer to independently certify the engine from the rest of the aircraft. This could make co-location of engine control functions with other aircraft functions problematic. However, it is interesting to note that advances have been made in other aircraft subsystems to mitigate cascading system failures, while still implementing integrated systems. Engine certification could, in the future, be performed using a surrogate supervisory controller, as it is now done for other integrated, flight critical systems. Working with the regulatory authorities, it should be possible to design more integrated engine and aircraft distributed architectures that not only retain adequate levels but enhance robustness against cascading failures. One such approach might utilize multiple levels of control redundancy, including retaining enough computational capability on-board the engine to allow reversionary control, even if all other systems on the aircraft fail. The result is an architecture that could improve system availability, redundancy, and fault tolerance as compared to conventional systems currently fielded.

Next Steps

DECWG is working to define system-level requirements for the use of “smart nodes” in distributed engine control system architectures, as well as detailed requirements for the affordable high-temperature capable nodes themselves. At the same time, notional smart nodes are being designed using currently available electronics and packaging – without adherence to cost targets – to understand technology and manufacturing gaps, and risks associated with closing those gaps.

Going forward, DECGW plans to begin to formulate paths towards solutions to close those gaps. The risks being identified will be prioritized in terms of cost and the ability of DECGW members to drive solutions. The risks identified in initial effort will be assessed using standard industry risk assessment tools. Items will be selected off of the list for development as funding sources are identified.

Risk mitigation will potentially involve high temperature electronic components such as field programmable gate arrays (FPGA), microprocessors, transient voltage suppressors, capacitors, and high temperature magnetic, as well as packaging elements such as printed wiring boards, mounting technologies, solders, masks, adhesive, and others. Based on this on-going learning, the requirements for the smart nodes will continue to be further detailed and refined.

Conclusion

The development of reliable, durable and especially affordable High Temperature Capable Electronics and Packaging provides the means to enable “smart” sensors and actuators that will enhance turbine engine performance, contribute toward increased use of Prognostic and Health Management (PHM) systems, and enable more comprehensive and lower cost to implement engine test cell Instrumentation. Associated innovation in communications and data management architectures that can provide the necessary data bandwidth within the computational constraints of these high temperature capable devices are a key to successful implementation of any distributed control system. As the high temperature electronics technology and manufacturing techniques continue to be advanced, distributed control systems will progress from limited use in cooler sections of the engine to pervasive use throughout the entire engine. Coordination and collaboration between all interested parties is key establishing requirements and executing a strategy for development of such high temperature capable electronics and packaging.

References

¹Behbahani, A., *Achieving AFRL Universal FADEC Vision with Open System Architecture Capability and Obsolescence for Military and Commercial Applications*, AIAA-2006-4302, 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Sacramento, California, July 9-12, 2006, Presented in May 2003. Presented as “Achieving Afrl Universal FADEC Vision” also at SAE E-36, Electronic Engine Controls Committee, Tampa, FL, March 7-9, 2006.

²Behbahani, A., *Adaptive Distributed Intelligent Control Architecture for Future Propulsion Systems*, MFPT Conference, Virginia Beach, April 2007.

³Tuleple, B., Behbahani, A., Millar, R. *Vision for Next Generation Modular Adaptive Generic Integrated Controls (MAGIC) For Military/Commercial Turbine Engines*, presented and published at JPC/AIAA 2007.

⁴John Rushby, SRI International, Menlo Park, California, A Comparison of Bus Architectures for Safety-Critical Embedded Systems, NASA/CR–2003–212161, National Aeronautics and Space Administration, Langley Research Center Hampton, Virginia, 23681–2199 March 2003.

⁵Behbahani, A. R., Culley, D., Smith, B. J., Darouse, C., Millar, R. C., Wood, B., Krodel, J., Carpenter, S., Mailander, W., Mahoney, T. D., Quinn, R., Bluish, C. P., Hegwood, B., Battestin, G., Roney, W., Rhoden, W., and Storey, W., “Status, Vision, and Challenges of an Intelligent Distributed Engine Control Architecture”, Society of Automotive Engineers Paper 2007-01-3859, Sept. 2007.

⁶Culley, D., Thomas, R., and Saus, J., “Concepts for Distributed Engine Control”, *43rd AIAA Joint Propulsion Conference & Exhibit*, AIAA 2007-5709 , 2007.

⁷Tulpule B., Behbahani A., “Distributed Open Software (DOS) Architectures for Control Systems”, *47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, AIAA 2011-6151.

⁸Behbahani A., Tulpule B., “Perspective for Distributed Intelligent Engine Controls of the Future”, *46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, AIAA 2010-6631.

⁹Yedavalli, R. K., Belapurkar, R. K., and Behbahani, A., “Design of Distributed Engine Control Systems for Stability Under Communication Packet Dropouts”, *AIAA Journal of Guidance, Control and Dynamics*, 32(5), pp.1544-1549, 2009.

¹⁰Walter Merril, Jong-Han Kim, Sanjay Lall, Steve Majerusiv, Daniel Howe, and Alireza Behbahani, “Distributed Engine Control Design Considerations”, Proceedings of the 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 28 July 2010.

¹¹P. L. Shaffer, General Electric Aircraft Engines, Distributed Control System for Turbine Engines, *J. Eng. Gas Turbines Power*, ASME, January 1999, Volume 121, Issue 1, 102 (6 pages), <http://dx.doi.org/10.1115/1.2816295>.